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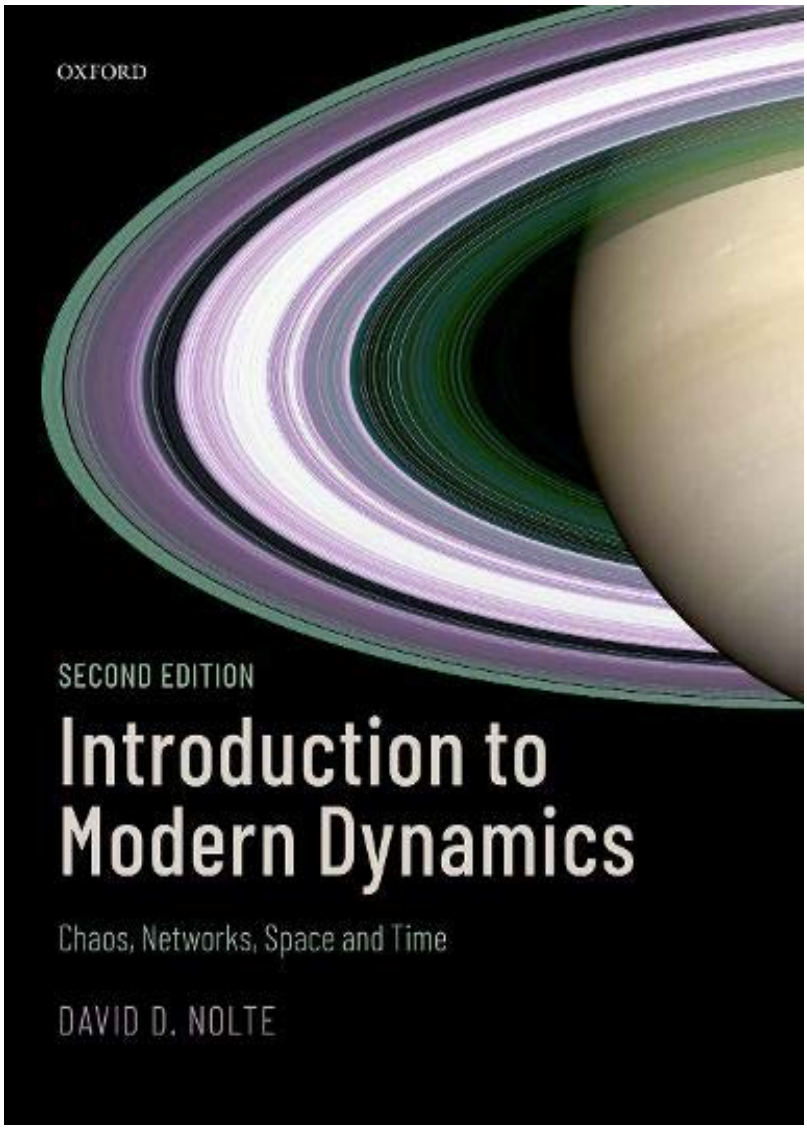

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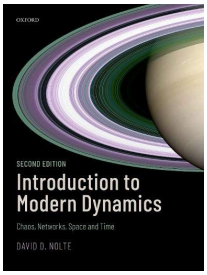

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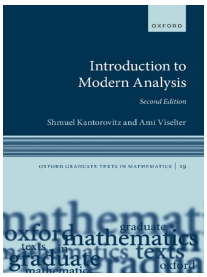

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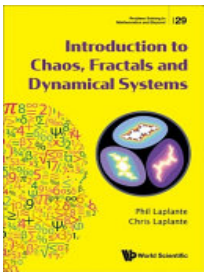

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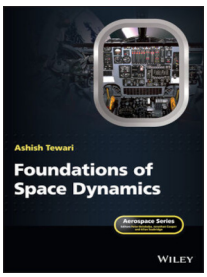

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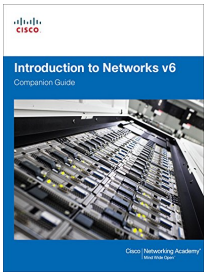

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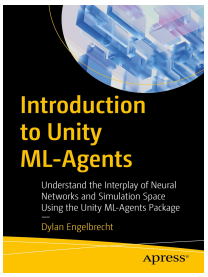

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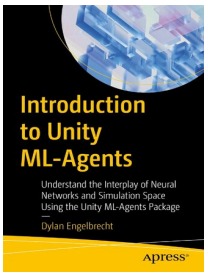

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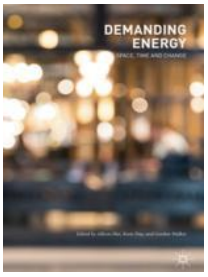

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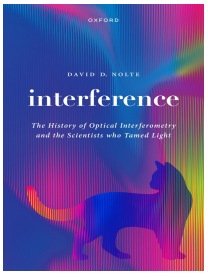

INTRODUCTION TO MODERN DYNAMICS

Introduction to Modern Dynamics

Chaos, Networks, Space and Time

Second Edition

David D. Nolte

Purdue University

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Preface to the Second Edition

Introduction to Modern Dynamics: Chaos, Networks, Space and Time (2015) is part of an emerging effort in physics education to update the undergraduate physics curriculum. Conventional junior-level mechanics courses have overlooked many modern dynamics topics that physics majors will use in their careers: nonlinearity, chaos, network theory, econophysics, game theory, neural nets, geodesic geometry, among others. These are the topics at the forefront of physics that drive high-tech businesses and start-ups where more than half of physicists are employed. The first edition of *Introduction to Modern Dynamics* contributed to this effort by introducing these topics in a coherent program that emphasized common geometric properties across a wide range of dynamical systems.

The second edition of *Introduction to Modern Dynamics* continues that trend by expanding chapters to including additional material and topics. It rearranges several of the introductory chapters for improved logical flow and expands them to add new subject matter. The second edition also has additional homework problems.

New or expanded topics in the second edition include

- Lagrangian applications
- Lagrange's undetermined multipliers
- Action-angle variables and conserved quantities
- The virial theorem
- Non-autonomous flows
- A new chapter on Hamiltonian chaos
- Rational resonances
- Synchronization of chaos
- Diffusion and epidemics on networks
- Replicator dynamics
- Game theory
- An extensively expanded chapter on economic dynamics

The goal of the second edition of *Introduction to Modern Dynamics* is to strengthen the sections on conventional topics (which students need for the GRE physics subject test), making it an ideal textbook for broader adoption at the junior

level, while continuing the program of updating topics and approaches that are relevant for the roles that physicists will play in the twenty-first century.

The historical development of modern dynamics is described in *Galileo Unbound: A Path Across Life, the Universe and Everything*, by D. D. Nolte, published by Oxford University Press (2018).

Preface: The Best Parts of Physics

The best parts of physics are the last topics that our students ever see. These are the exciting new frontiers of nonlinear and complex systems that are at the forefront of university research and are the basis of many of our high-tech businesses. Topics such as traffic on the World Wide Web, the spread of epidemics through globally mobile populations, or the synchronization of global economies are governed by universal principles just as profound as Newton's Laws. Nonetheless, the conventional university physics curriculum reserves most of these topics for advanced graduate study. Two justifications are given for this situation: first, that the mathematical tools needed to understand these topics are beyond the skill set of undergraduate students, and second, that these are specialty topics with no common theme and little overlap.

Introduction to Modern Dynamics: Chaos, Networks, Space and Time dispels these myths. The structure of this book combines the three main topics of modern dynamics—chaos theory, dynamics on complex networks and the geometry of dynamical spaces—into a coherent framework. By taking a geometric view of physics, concentrating on the time evolution of physical systems as trajectories through abstract spaces, these topics share a common and simple mathematical language with which any student can gain a unified physical intuition. Given the growing importance of complex dynamical systems in many areas of science and technology, this text provides students with an up-to-date foundation for their future careers.

While pursuing this aim, *Introduction to Modern Dynamics* embeds the topics of modern dynamics—chaos, synchronization, network theory, neural networks, evolutionary change, econophysics, and relativity—within the context of traditional approaches to physics founded on the stationarity principles of variational calculus and Lagrangian and Hamiltonian physics. As the physics student explores the wide range of modern dynamics in this text, the fundamental tools that are needed for a physicist's career in quantitative science are provided, including topics the student needs to know for the Graduate Record Examination (GRE). The goal of this textbook is to modernize the teaching of junior-level dynamics, responsive to a changing employment landscape, while retaining the core traditions and common language of dynamics texts.

A unifying concept: geometry and dynamics

Instructors or students may wonder how an introductory textbook can contain topics, under the same book cover, on econophysics and evolution as well as the physics of black holes. However, it is not the physics of black holes that matters, rather it is the description of general dynamical spaces that is important and the understanding that can be gained of the geometric aspects of trajectories governed by the properties of these spaces. All changing systems, whether in biology or economics or computer science or photons in orbit around a black hole, are understood as trajectories in abstract dynamical spaces.

Newton takes a back seat in this text. He will always be at the heart of dynamics, but the modern emphasis has shifted away from $F = ma$ to a newer perspective where Newton's Laws are special cases of broader concepts. There are economic forces and forces of natural selection that are just as real as the force of gravity on point particles. For that matter, even the force of gravity recedes into the background as force-free motion in curved space-time takes the fore.

Unlike Newton, Hamilton and Lagrange retain their positions here. The variational principle and the minimization of dynamical quantities are core concepts in dynamics. Minimization of the action integral provides trajectories in real space, and minimization of metric distances provides trajectories—geodesics—in dynamical spaces. Conservation laws arise naturally from Lagrangians, and energy conservation enables simplifications using Hamiltonian dynamics. Space and geometry are almost synonymous in this context. Defining the space of a dynamical system takes first importance, and the geometry of the dynamical space then determines the set of all trajectories that can exist in it.

A common tool: dynamical flows and the ODE solver

A mathematical flow is a set of first-order differential equations that are solved using as many initial values as there are variables, which defines the dimensionality of the dynamical space. Mathematical flows are one of the foundation stones that appears continually throughout this textbook. Nearly all of the subjects explored here—from evolving viruses to orbital dynamics—can be captured as a flow. Therefore, a common tool used throughout this text is the numerical solution of the ordinary differential equation (ODE). Computers can be both a boon and a bane to the modern physics student. On the one hand, the easy availability of ODE solvers makes even the most obscure equations easy to simulate numerically, enabling any student to plot a phase plane portrait that contains all manner of behavior. On the other hand, physical insight and analytical understanding of complex behavior tend to suffer from the computer-game nature of simulators. Therefore, this textbook places a strong emphasis on analysis, and on behavior

under limiting conditions, with the goal to reduce a problem to a few simple principles, while making use of computer simulations to capture both the whole picture as well as the details of system behavior.

Traditional junior-level physics: how to use this book

All the traditional topics of junior-level physics are here. From the simplest description of the harmonic oscillator, through Lagrangian and Hamiltonian physics, to rigid body motion and orbital dynamics—the core topics of advanced undergraduate physics are retained and are interspersed throughout this textbook.

What's simple in complex systems?

The traditional topics of mechanics are integrated into the broader view of modern dynamics that draws from the theory of complex systems. The range of subject matter encompassed by complex systems is immense, and a comprehensive coverage of this topic is outside the scope of this book. However, there is still a surprisingly wide range of complex behavior that can be captured using the simple concept that the geometry of a dynamic space dictates the set of all possible trajectories in that space. Therefore, simple analysis of the associated flows provides many intuitive insights into the origins of complex behavior. The special topics covered in this textbook are:

- Chaos theory (Chapter 4)

Much of nonlinear dynamics can be understood through *linearization* of the *flow* equations (equations of motion) around special *fixed points*. Visualizing the dynamics of multi-parameter systems within multidimensional spaces is made simpler by concepts such as the *Poincaré section*, *strange attractors* that have *fractal geometry*, and *iterative maps*.

- Synchronization (Chapter 6)

The nonlinear *synchronization* of two or more oscillators is a starting point for understanding more complex systems. As the whole can be greater than the sum of the parts, global properties often emerge from local interactions among the parts. Synchronization of oscillators is surprisingly common and robust, leading to *frequency-entrainment*, *phase-locking*, and *fractional resonance* that allow small perturbations to control large networks of interacting systems.

- Network theory (Chapter 7)

Everywhere we look today, we see networks. The ones we interact with daily are social networks and related networks on the World Wide Web. In this chapter, individual nodes are joined into networks of various geometries, such as *small-world networks* and *scale-free networks*. The *diffusion* of disease across these networks is explored, and the synchronization of *Poincaré phase oscillators* can induce a *Kuramoto transition* to complete synchronicity.

- Evolutionary dynamics (Chapter 8)

Some of the earliest explorations of nonlinear dynamics came from studies of *population dynamics*. In a modern context, populations are governed by evolutionary pressures and by genetics. Topics such as viral mutation and spread, as well as the evolution of species within a *fitness landscape*, are understood as simple balances within *quasispecies* equations.

- Neural networks (Chapter 9)

Perhaps the most complex of all networks is the brain. This chapter starts with the single neuron, which is a *limit-cycle oscillator* that can show interesting *bistability* and *bifurcations*. When neurons are placed into simple neural networks, such as *perceptrons* or *feedforward networks*, they can do simple tasks after training by *error back-propagation*. The complexity of the tasks increases with the complexity of the networks, and *recurrent networks*, like the *Hopfield neural net*, can perform associated memory operations that challenge even the human mind.

- Econophysics (Chapter 10)

A most baffling complex system that influences our daily activities, as well as the trajectory of our careers, is the economy in the large and the small. The dynamics of *microeconomics* determines what and why we buy, while the dynamics of *macroeconomics* drives entire nations up and down economic swings. These forces can be (partially) understood in terms of nonlinear dynamics and flows in economic spaces. *Business cycles* and the diffusion of prices on the *stock market* are no less understandable than evolutionary dynamics (Chapter 8) or network dynamics (Chapter 7), and indeed draw closely from those topics.

- Geodesic motion (Chapter 11)

This chapter is the bridge between the preceding chapters on complex systems and the succeeding chapters on relativity theory (both special and general). This is where the geometry of space is first fully defined in terms of a *metric tensor*, and where trajectories through a *dynamical space* are discovered to be paths of *force-*

free motion. The *geodesic equation* (a geodesic flow) supersedes Newton's Second Law as the fundamental equation of motion that can be used to define the path of masses through potential landscapes and the path of light through space-time.

- Special relativity (Chapter 12)

In addition to traditional topics of *Lorentz transformations* and *mass-energy* equivalence, this chapter presents the broader view of trajectories through Minkowski *space-time* whose geometric properties are defined by the *Minkowski metric*. Relativistic forces and noninertial (accelerating) frames connect to the next chapter that generalizes all relativistic behavior.

- General relativity (Chapter 13)

The physics of *gravitation*, more than any other topic, benefits from the overarching theme developed throughout this book—that the geometry of a space defines the properties of all trajectories within that space. Indeed, in this geometric view of physics, Newton's force of gravity disappears and is replaced by force-free geodesics through *warped* space-time. Mercury's orbit around the Sun, and trajectories of light past *black holes*, are elements of geodesic flows whose properties are easily understood using the tools developed in Chapter 4 and expanded upon throughout this textbook.

Acknowledgments

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Part I

Geometric Mechanics

Traditional approaches to the mechanics of particles tend to focus on individual trajectories. In contrast, modern dynamics takes a global view of dynamical behavior by studying the set of all possible trajectories of a system. Modern dynamics furthermore studies properties in dynamical spaces that carry names like *state space*, *phase space*, and *space–time*. Dynamical spaces can be highly abstract and can have high dimensionality. This initial part of the book introduces the mathematical tools necessary to study the geometry of dynamical spaces and the resulting dynamical behavior within those spaces. Central to modern dynamics is Hamilton's Principle of Stationary Action as the prototypical minimization principle that underlies much of dynamics. This approach will lead ultimately (in Part III) to the geodesic equation of general relativity, in which matter warps Minkowski space (space–time), and trajectories execute force-free motion through that space.

Physics and Geometry

1

Foucault's Pendulum in the Pantheon in Paris

Modern dynamics, like classical dynamics, is concerned with trajectories through space—the descriptions of trajectories (kinematics) and the causes of trajectories (dynamics). However, unlike classical mechanics, which emphasizes motions of physical masses and the forces acting on them, modern dynamics generalizes the notion of trajectories to encompass a broad range of time-varying behavior that goes beyond material particles to include animal species in ecosystems, market prices in economies, and virus spread on connected networks. The spaces that these trajectories inhabit are abstract, and can have a high number of dimensions. These generalized spaces may not have Euclidean geometry, and may be curved like the surface of a sphere or space–time warped by gravity. The central object of interest in dynamics is the evolving state of a system. The state description of a system must be unambiguous, meaning that the next state to develop in time is

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uniquely determined by the current state. This is called deterministic dynamics, which includes deterministic nonlinear dynamics for which chaotic trajectories may have an apparent randomness to their character.

This chapter lays the foundation for the description of dynamical systems that move continuously from state to state. Families of trajectories, called dynamical flows, are the fundamental elements of interest; they are the field lines of dynamics. These field lines are to deterministic dynamics what electric and magnetic field lines are to electromagnetism. One key difference is that there is only one set of Maxwell's equations, while every nonlinear dynamical system has its own set of equations, providing a nearly limitless number of possibilities for us to study.

This chapter begins by introducing general ideas of trajectories as the set of all possible curves defined by dynamical flows in state space. To define trajectories, we will establish notation to help us describe high-dimensional, abstract, and possibly curved spaces. This is accomplished through the use of matrix (actually tensor) indices that look strange at first to a student familiar only with vectors, but which are convenient devices for keeping track of multiple coordinates. The next step constructs coordinate transformations from one coordinate system to another. For instance, a central question in modern dynamics is how two observers, one in each system, describe the common phenomena that they observe. The *physics* must be invariant to the choice of coordinate frame, but the descriptions can differ widely.

1.1 State space and dynamical flows

Configuration space is defined by the spatial coordinates needed to describe a dynamical system. The path the system takes through configuration space is its trajectory. Each point on the trajectory captures the successive configurations of the system as it evolves in time. However, knowing the current configuration of the system does not guarantee that the next configuration can be defined. For instance, the trajectory can loop back and cross itself. The velocity vector that pointed one direction at the earlier time can point in a different direction at a later time. Therefore, a velocity vector must be attached to each configuration to define how it will evolve next.

1.1.1 State space

By adding velocities, associated with each of the coordinates, to the configuration space, a new expanded space, called *state space*, is created. For a given initial condition, there is only a single system trajectory through this multidimensional space, and each point on the trajectory uniquely defines the next state of the system.[1] This trajectory in state space can cross itself only at points where all the velocities vanish, otherwise the future state of the system would not be unique.

[1] See A. E. Jackson, *Perspectives of Nonlinear Dynamics* (Cambridge University Press, 1989).

Example 1.1 State space of the damped one-dimensional harmonic oscillator

The damped harmonic oscillator in one coordinate has the single second-order ordinary differential equation[2]

$$m\ddot{x} + \gamma\dot{x} + kx = 0 \tag{1.1}$$

where m is the mass of the particle, γ is the drag coefficient, and k is the spring constant. Any set of second-order time-dependent ordinary differential equations (e.g., Newton's second law) can be written as a larger set of first-order equations. For instance, the single second-order equation (1.1) can be rewritten as two first-order equations

$$\begin{aligned} \dot{x} &= v \\ m\dot{v} + \gamma v + kx &= 0 \end{aligned} \tag{1.2}$$

It is conventional to write these with a single time derivative on the left as

$$\begin{aligned} \dot{x} &= v \\ \dot{v} &= -2\beta v - \omega_0^2 x \end{aligned} \tag{1.3}$$

in the two variables (x, v) with $\beta = \gamma/2m$ and $\omega_0^2 = k/m$. *State space* for this system of equations consists of two coordinate axes in the two variables (x, v), and the right-hand side of the equations are expressed using only the same two variables.

To solve this equation, assume a solution in the form of a complex exponential evolving in time with an angular frequency ω as (see Appendix A.1)

$$x(t) = Xe^{i\omega t} \tag{1.4}$$

Insert this expression into Eq. (1.1) to yield

$$-m\omega^2 Xe^{i\omega t} + i\omega\gamma Xe^{i\omega t} + kXe^{i\omega t} = 0 \tag{1.5}$$

with the characteristic equation

$$\begin{aligned} 0 &= m\omega^2 - i\omega\gamma - k \\ &= \omega^2 - i2\omega\beta - \omega_0^2 \end{aligned} \tag{1.6}$$

where the damping parameter is $\beta = \gamma/2m$, and the resonant angular frequency is given by $\omega_0^2 = k/m$. The solution of the quadratic equation (1.6) is

$$\omega = i\beta \pm \sqrt{\omega_0^2 - \beta^2} \tag{1.7}$$

Using this expression for the angular frequency in the assumed solution (1.4) gives

$$x(t) = X_1 \exp(-\beta t) \exp\left(i\sqrt{\omega_0^2 - \beta^2}t\right) + X_2 \exp(-\beta t) \exp\left(-i\sqrt{\omega_0^2 - \beta^2}t\right) \tag{1.8}$$

Consider the initial values $x(0) = A$ and $\dot{x}(0) = 0$; then the two initial conditions impose the values

[2] The "dot" notation stands for a time derivative: $\dot{x} = dx/dt$ and $\ddot{x} = d^2x/dt^2$. It is a modern remnant of Newton's fluxion notation.

Example 1.1 *continued*

$$X_1 = \frac{A}{2}\left(\frac{\sqrt{\omega_0^2 - \beta^2} - i\beta}{\sqrt{\omega_0^2 - \beta^2}}\right)$$
$$X_2 = \frac{A}{2}\left(\frac{\sqrt{\omega_0^2 - \beta^2} + i\beta}{\sqrt{\omega_0^2 - \beta^2}}\right) = X_1^* \tag{1.9}$$

The final solution is

$$x(t) = A\exp(-\beta t)\left[\cos\left(\sqrt{\omega_0^2 - \beta^2 t}\right) + \frac{\beta}{\sqrt{\omega_0^2 - \beta^2}}\sin\left(\sqrt{\omega_0^2 - \beta^2 t}\right)\right] \tag{1.10}$$

which is plotted in Fig. 1.1(a) for the case where the initial displacement is a maximum and the initial speed is zero. The oscillator "rings down" with the exponential decay constant β. The angular frequency of the ring-down is not equal to ω_0, but is reduced to the value $\sqrt{\omega_0^2 - \beta^2}$. Hence, the damping decreases the frequency of the oscillator from its natural resonant frequency. A system trajectory in state space starts at an initial condition (x_0, v_0), and uniquely traces the time evolution of the system as a curve in the state space. In Fig. 1.1(b), only one trajectory (stream line) is drawn, but streamlines fill the state space, although they never cross, except at singular points where all velocities vanish. Streamlines are the field lines of the vector field. Much of the study of modern dynamics is the study of the geometric properties of the vector field (tangents to the streamlines) and field lines associated with a defined set of flow equations.

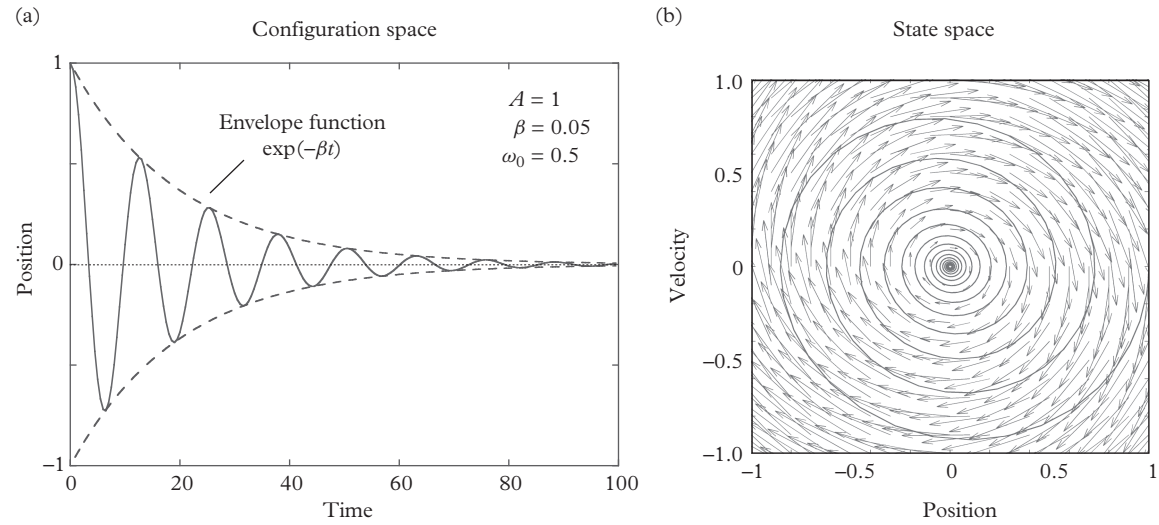


Figure 1.1 *Trajectories of the damped harmonic oscillator. (a) Configuration position versus time. (b) State space, every point of which has a tangent vector associated with it. Streamlines are the field lines of the vector field and are dense. Only a single streamline is shown.*

Exploring the Variety of Random Documents with Different Content

snows of the Gennargentu and the rains which descend on the western mountain slopes. Other rivers of equal length are hardly more than torrents, which at one time invade the fields adjoining them, and at another shrink to a thin thread of water meandering between thickets of laurel-trees. Most of the river beds are dry during eight months of the year, and even after rain the water does not find its way into the sea, but is absorbed by the littoral swamps.

All these swamps have brackish water. The largest amongst them communicate freely with the sea, at least during the rainy season, but others are separated from it by a strip of sand. But these, too, are brackish, for the sea-water percolates through the soil, and keeps them at the same level. The water of the inland swamps is likewise saturated with saline substances derived from the surrounding soil. They generally dry up in summer, but the coating of salt which then appears is hardly dry enough to repay the labour of collection and refinement. The only salt marshes actually exploited are those of Cagliari and of Carlo-Forte, on San {342} Pietro. They have been leased to a French company, and yield annually nearly 120,000 tons of salt.

Swamps and marshes envelop nearly the whole of the island in a zone of miasmata, which are carried by the wind into the interior, producing fever even in the more elevated mountain districts. There are localities on the island the air of which no stranger can breathe with impunity. The coast districts of Sardinia, with their stagnant waters, are, in truth, the most unhealthy in Italy, and quite one-fourth of the area of the island is exposed to the scourge of malaria, which sufficiently accounts for the small population of the island and the little progress made.

Even when Sardinia was at the height of its prosperity, and supplied Rome with an abundance of corn, cheese, pork, lead, copper, iron, and textile fabrics, it was noted for its unhealthiness, and the emperors exiled to it those whom they desired to get rid of. Then, as now, the landed proprietors, about the middle of June,

retired to the towns, the walls of which offered some protection against the poisonous air. The Italian Government officials are sent to the island as a punishment, and for the most part look upon themselves as condemned to death. Even the native villagers are bound to observe the greatest precautions, and wear garments of skin or leather which are impenetrable to rain, mist, and dew. They are dressed most warmly during the hottest part of the year as a protection against the climate, and in their long *mastrucas* of sheepskin they almost look like Wallachian herdsmen.

Ancient geographers, as well as the Sardinians themselves, ascribe the unhealthiness of the climate to the rarity of north-easterly winds. The mountains of Limbarra, in the north of the island, are popularly supposed to act as a sort of screen, which diverts this health-bringing wind, to the great detriment of Lower Sardinia; and there appears to be much truth in this popular notion. South-westerly winds, or *libeccios*, are almost equally rare, and when they blow they do so with tempestuous violence.

The regular winds of Sardinia blow from the north-west or south-east. The former is known as the *maestrale*, the latter as the *levante* or *sirocco*, called *maledetto levante* by the inhabitants of Southern Sardinia. It becomes charged with moisture during its passage across the Mediterranean, and its temperature is in reality much less than might be supposed from the lassitude produced by it. The maestrale, on the other hand, is hailed with joy, for it is an invigorating wind. On reaching the coast it generally parts with its moisture, and when it arrives at Cagliari it is perfectly dry. The capital of Sardinia is indebted to this wind and to sea breezes for its low temperature (62·4° F.), which is far lower than that of Genoa.

Hurricanes are comparatively rare, and hailstorms, which work such damage elsewhere, are hardly known. Most of the rain falls in autumn; it ceases in December, when the pleasantest season sets in. These are the "halcyon days" of ancient poets, when the sea calms down in order that the sacred bird may build his nest. But these

pleasant days are succeeded by a wretched spring. February, the "double-faced month" of Sardinian mariners, brings capricious frosts, to which {343} succeed, in March and April, abrupt changes of temperature, winds, and rain. Vegetation in consequence is far more backward than might be supposed from the latitude.

The vegetation of Sardinia resembles that of the other islands of the Mediterranean. The forest in the highland valleys of the interior and on the trackless mountain slopes consists of pines, oaks, and holm-oaks, mixed here and there with yoke-elms and maples. The villages are surrounded by chestnut-trees and groves of magnificent walnut-trees. The hill-tops, robbed of their forests, are covered with odoriferous plants and thickets of myrtles, strawberry-trees, and heather. It is there the bees collect the bitter honey so much despised by Horace. Vast tracts of uncultivated land near the seashore are covered with wild olive-trees, which only need grafting to yield excellent fruit. All the fruit trees and useful plants of the Mediterranean flourish in Sardinia. Almond and orange trees, introduced by the Moors at the close of the eleventh century, flourish vigorously. The orange groves of Millis, which are protected by the extinct volcano of Monte Ferru, are, perhaps, the most productive on the shores of the Mediterranean, and in good seasons yield 60,000,000 oranges. The gardens of Domus Novas, Ozieri, and Sassari are of surprising fertility. In the southern part of the island, wherever the cultivated fields gain upon the lands covered with rock-roses, fennel, and lilies, they are fenced in with fig-trees. The fan-shaped foliage of the date-palm is seen near every town, and more especially in the environs of Cagliari. By a curious contrast the dwarf palm is not met with in the southern lowlands of the island, though their climate is almost African, but forms dense thickets in the solitudes of Alghero, in the north of the islands. The inhabitants eat the roots of this tree, as do also the Moors.

Although all the plants of neighbouring countries become easily acclimatized in Sardinia, that island is naturally poorer in species

than are continental regions lying under the same latitude. There is nothing special about its flora, for the island is probably only a remnant of a larger tract of land which formerly joined Europe to Africa. As to the famous plant mentioned by ancient writers, which, eaten by mistake, produced fits of "sardonic laughter," or even death, it does not appear to be peculiar to the island. Mimaut thinks, from the descriptions of Pliny and Pausanias, that the large-leafed water-parsley (*Sium latifolium*) is referred to.

The number of species of animals, like that of plants, is smaller in Sardinia than on the neighbouring continent. There are neither bears, badgers, polecats, nor moles. Vipers or venomous serpents of any description do not exist, and the only animal to be dreaded is the tarentula (*arza*, or *argia*), a sting from which can be cured only by dancing until completely exhausted, or by immersion in dung. The ordinary frog, though common in Corsica, does not exist, but European butterflies are numerous. The *moufflon*, which is, perhaps, the ancestor of our domestic sheep, and has been exterminated in nearly all the islands of the Mediterranean, still lives in the mountains of Corsica and Sardinia. Wild horses roamed over Sant' Antioco as recently as the beginning of this century; myriads {344} of rabbits burrow in the small islands lining the coast; and wild goats with long horns and yellow teeth inhabit the limestone island of Tavolara, in the Gulf of Terranova. These goats are descended from domestic animals abandoned at some former period. Caprera, the residence of Garibaldi, is named after the goats which formerly inhabited it, and animals of that kind recently introduced there quickly returned to a state of nature.

Naturalists have observed that the mammals of Sardinia are smaller than the same species living on the continent. The goat is the only exception to the rule. The stag, deer, wild boar, fox, wild cat, hare, rabbit, marten, and weasel are all of them smaller than the continental varieties. The same rule applies to domesticated animals, with the exception of the pig, which grows to a great size,

especially where it is allowed to roam through oak forests. There is a variety of this animal whose hoofs are not cloven, and which ought, therefore, to be classed amongst solipeds. The horses and asses of Sardinia are dwarfs. But the horse is distinguished by great sobriety, sureness of foot, vigour, and endurance. If in addition to these advantages it possessed a more attractive exterior, it would rank among the most highly appreciated horses of Europe. As to the donkeys, though hardly larger than a mastiff, they are brave little animals, and frequently share with their masters the only room of their abode. The old-fashioned mills, resembling in every respect the Roman bas-reliefs which may be seen in the Vatican, are propelled by these donkeys, which thus materially contribute towards the support of their proprietors.

Sardinia abounds more than any other country of Western Europe in prehistoric remains. There are megaliths, known as "giants' stones," "altars," or "long-stones," as in Brittany, scarcely any of them showing traces of the chisel. Dolmens, however, are rare, and the genuineness of all is doubted. Amongst these monuments there are, perhaps, some which were connected with the worship of some Eastern deity, for Phœnicians and Carthaginians stayed for a considerable time upon the island, where they founded Caralis, Nora, Tharros, and other towns; and even during the time of the Romans it was customary to place Punic inscriptions upon the tombstones. The ruins of Tharros have yielded golden idols and other articles in large numbers, most of them being of Egyptian origin. But the principal witnesses to the civilisation of the ancient Sards are the curious structures known as *nuraghi*. They generally occupy the hill-tops, and, seen from a distance, resemble pyramids. The limestone plateau of Giara, near the centre of the island, is surrounded by masonry structures of this description, which abound also in other portions of the island, the number still existing being nearly 4,000. They are most numerous in the basaltic region to the south of

Macomer, and are met with for the most part in fertile districts, far away from the arid steppes.

The origin and uses of these nuraghi have been a subject of much discussion, but archæologists now almost universally adopt the views of Signor Spano, the indefatigable explorer of Sardinian antiquities. According to him these nuraghi were dwellings, and their Phœnician name simply means "round house." The rudest {345} among them, dating back probably for forty centuries, contain but a single chamber. They were erected during the age of stone, when man first gave up his cavern dwellings. The more recent constructions date back to the age of bronze, and even of iron. More skill is exhibited in their structure, though no mortar has been used, and they contain two or more chambers, forming as many floors, and accessible by means of stone stairs. The ground floor of some is large enough for the accommodation of forty or fifty persons, and is furnished with antechambers and small semicircular recesses. The nuraghi of Su Domu or S'Orcu, near Domus Novas, which has recently been demolished, contained ten chambers and four courtyards; it was a fortress as well as a dwelling-place, capable of accommodating a hundred persons and standing a siege. The dwellings of the modern Albanians and of the Swaneti in the Caucasus still resemble these ancient abodes.

Fig. 127—La Giara. M
Scale 1 : 308,640.

The rubbish which accumulated in these nuraghi has yielded a multitude of objects which throw light upon the daily life of the inhabitants, and bear witness to their relative civilisation. The lower strata only contain hand-made utensils, stone arms, and pottery, but in the upper and more recent layers many articles of bronze have been found. Other monuments of cyclopean structure stand near these ancient dwellings. They are popularly known as "giants' tombs," and Signor {346} Sapi, who has examined a large number of them, has discovered in every instance the ashes of human beings.

Though very superstitious, the Sardinians have no legends respecting these dwellings of the aborigines, and at most attribute

them to the devil. This absence of traditions is no doubt traceable to the almost total annihilation of the inhabitants by successive conquerors. The Carthaginians showed no mercy to the aborigines, and during the first centuries of Roman rule massacres and forcible emigration were the order of the day, and the gaps thus created were filled up by Italian colonists and exiles.

The ancient Sards were most likely Iberians. They are of low stature, and the climate, which has stunted the growth of wild and domesticated animals, appears to have influenced man likewise; but they are well proportioned and muscular, have an abundance of black hair and strong beards, and scarcely ever grow bald. There are minor differences in the Sards of the two provinces. Those of the north have generally oval features and an aquiline nose, whilst those near Cagliari, who are probably more mixed, have irregular features and prominent cheek-bones.

The inhabitants of the interior of the island are, perhaps, of purer race than any other Europeans. Their ancestors, no doubt, were of the most diverse origin, but most invasions which took place after the Roman era stopped short at the coast. The Vandals paid a visit to Sardinia, but all the other Germanic tribes, who ravaged nearly every other country of Western Europe, spared that island, and its inhabitants were thus able to preserve their manners and language. The Moors, Pisans, Genoese, Catalonians, and Spaniards, who successively invaded the island, never penetrated beyond the coast. There is only one exception to this rule, viz. that of the Barbaricini, who inhabit the mountain district of Barbagia, in the very centre of the island, and who are supposed to be the descendants of Berbers expelled from Africa by the Vandals. When they came to the island they were still pagans, and they intermarried with their neighbours, the Ilienses, an aboriginal tribe, pagans like themselves. They were converted to Christianity in the seventh century, and the sombre dress worn by their women reminds us of Barbary.

Of all the idioms derived from the Latin, that spoken in Sardinia has most resemblance to the language of the ancient Romans. More than five hundred words are absolutely identical. There are likewise a few Greek words not met with in any other Latin idiom, as well as two or three words which have no affinity with any other European tongue, and which are, perhaps, derived from the language spoken by the aborigines. The two leading dialects, those of Logoduro, in the north, and of Cagliari, are directly derived from the Latin, and are, perhaps, most nearly related to Spanish. At Sassari, and in some of the neighbouring coast districts, an Italian dialect is spoken which is very much like that of Corsica or Genoa. At Alghero the descendants of the Catalonian immigrants who settled there about the middle of the fourteenth century still speak their old Provençal. The *Maurelli*, or *Maureddus*, in the environs of Iglesias, who are probably Berbers, {347} and can be recognised by their narrow skulls, make use of a few African words. Maltzan looks upon the inhabitants of the fertile district of Millis as the purest representatives of African immigrants, and it was they who introduced the cultivation of the orange into Sardinia.

The Sardinians of the interior not only retain their ancient language, but likewise many of their ancient customs. Their dances are still the same as in the time of Greece. In the north the steps are regulated by the human voice, the chanters occupying the centre of the ring. In the south a musical instrument, the *launedda*, is used, which is nothing but an ancient flute, made of two or three reeds. The customs observed at christenings, weddings, and funerals are likewise of remote date. Marriage, as amongst nearly all the ancient inhabitants of Europe, is preceded by a feigned abduction of the bride. The latter, after she has entered the house of her husband, must not stir from her place during that day, nor speak a single word. Mute as a statue, she is no longer a sentient being, but a "thing," the property of her husband. She is not permitted to see her

relatives during three days, and in the south many women partly conceal their features.

The mountaineers likewise observe the lugubrious ceremony of a wake, called *titio* or *attito*. Women, who are either the friends of the deceased or are engaged for the purpose, penetrate the mortuary chamber, tear their hair, howl, and improvise hymns of mourning. These old pagan ceremonies become truly terrific when the deceased has been the victim of assassination, for in that case the mourners swear to take the life of the murderer. Up to the beginning of this century the practice of the vendetta annually cost the lives of hundreds of young men. At the present day it is confined to the most secluded parts of the island, and in the mountain districts of Nuoro and La Gallura it is customary at christenings to place a few bullets in the swaddling-clothes of the infants, these consecrated bullets being supposed never to miss their mark. Another custom still more barbarous has ceased to be observed since the beginning of the last century. Women, called "finishers" (*accabadure*), were employed to hasten the end of dying persons, a practice which often led to the most atrocious deeds.

The peasant of Sardinia, though not the proprietor of the soil, is nevertheless permitted to enjoy the result of his labour. The feudal system existed up to 1840, and many traces of it still survive. The great barons, most of them of Spanish extraction, were almost the absolute masters of the country, and up to 1836 they administered the law, had their prisons, and erected gallows as a symbol of their power. The peasants, however, were not tied to the land, but could migrate at pleasure, and custom granted them a fair share of the produce of the soil. By virtue of an *ademprivio* they were permitted to cut wood in the forests, to pasture their sheep on the hills, and to bring into cultivation the waste lands of the plains. Agriculture was carried on in the most primitive fashion, for the great lords of the land usually resided abroad, and the management of their estates was left to bailiffs. Government has now become the proprietor of

most of the unenclosed {348} land, 80,000 acres of which have been ceded to the Anglo-Italian Company, which has undertaken to provide the island with a network of railways.

Fig. 128.—DISTRICT OF IGLESIAS. M
Scale 1 : 420,800.

In the more densely populated districts the division of the land is exceedingly minute, and this subdivision is still progressing at a most disastrous rate. The nomad herdsmen, on the other hand, possess no land of their own, though, if inclined, they are at liberty to enclose a plot. But vague proprietary rights like these render the careful cultivation of the soil impossible. It has been seriously

proposed to expropriate the whole of the land, and to sell it to a few enterprising capitalists, but this would simply amount to a restoration of the old feudal times, and poverty, which is great even now, would become greater. There are villages in the district of Ogliastra where the peasants eat bread made of the acorns of *Quercus ilex*, the dough being kneaded with water containing a fatty clay. This is, perhaps, the only instance of earth-eating in Europe. The Spaniards, too, eat acorn bread, but they use the fruit of *Quercus ballota*, which is really edible, and are careful not to mix its flour with earth.

The Sardinians, even when they are the owners of pasture-grounds or of fields, never live in the country. Like the Sicilians, they are concentrated in towns or large villages, and neither hamlets nor isolated farmhouses are met with. Even {349} the shepherds in the mountains build their huts in groups called *stazzi*, and combine for mutual protection into *cussorgie*. Members of these associations, when they lose their cattle from disease or any other cause, may claim one or more beasts from every one of their comrades living within the same district or canton. In other parts of the island—as, for instance, near Iglesias—the produce of the orchards is looked upon as common property. The mountaineers, though poor, practise the ancient virtue of hospitality, and though the dwellings are rude, they find means of making a stranger staying amongst them comfortable.

The products of Sardinia form but a small proportion of those of all Italy. Most of the peasants only work by fits and starts, and hardly more than a fourth of the area of the island has been brought under cultivation. It sometimes happens that the crops are destroyed by the scorching heat of the sun, or eaten up by locusts, which come in swarms from Africa. Except near Sassari no attempt is made to improve the produce. The olive-tree alone is cultivated with some care, for the grower of a certain number of these trees may claim political privileges, and even the title of "Count," and

thousands of proprietors have converted their sterile steppes into productive olive groves. The millions of oranges grown in the gardens of Millis and elsewhere are taken entirely for home consumption. Commercially these oranges are of less importance than the saline plants collected in the marshes of the coast districts, and the ashes of which are exported to Marseilles to be converted into soda.

The working of granite and marble quarries yields some profit, but the mines, which were of such importance in the time of the Romans, are hardly touched now. There is only one iron mine, that of San Leone, where work has been carried on seriously by a French company since 1822. It yields about 50,000 tons of ore annually, and the oldest railway of the island connects that mine with Cagliari. The district of Iglesias, where the Romans founded Plumbea and Metalla, and the Pisans searched for silver, has recently regained some of its ancient importance on account of its lead and zinc mines. The waste of the old mines is likewise being scientifically treated by French, English, and Italian companies, to whom mining claims have been ceded, and a curious stalactite cavern which traverses the hill near Domus Novas has been utilised in gaining access to the scoriæ. Iglesias is rapidly growing into a city of modern aspect, the village of Gonessa is already a respectable town, and the little harbour of Porto Scuso, until recently almost deserted, is now crowded with small craft employed in carrying annually 900,000 tons of lead and zinc ore to the roadstead of Carlo-Forte. Unfortunately the miners, especially those from abroad, frequently succumb to the climate.

The fisheries, being for the most part carried on in the bays exposed to the sea breezes, are not attended by the same dangers. Certain portions of the coast abound in fish, such as the Bay of Cagliari, and the narrow arms of the sea in the archipelago of the Maddalena, which the ancients searched for purple shells. Anchovies and “sardines” periodically visit the coasts, and as many as 50,000

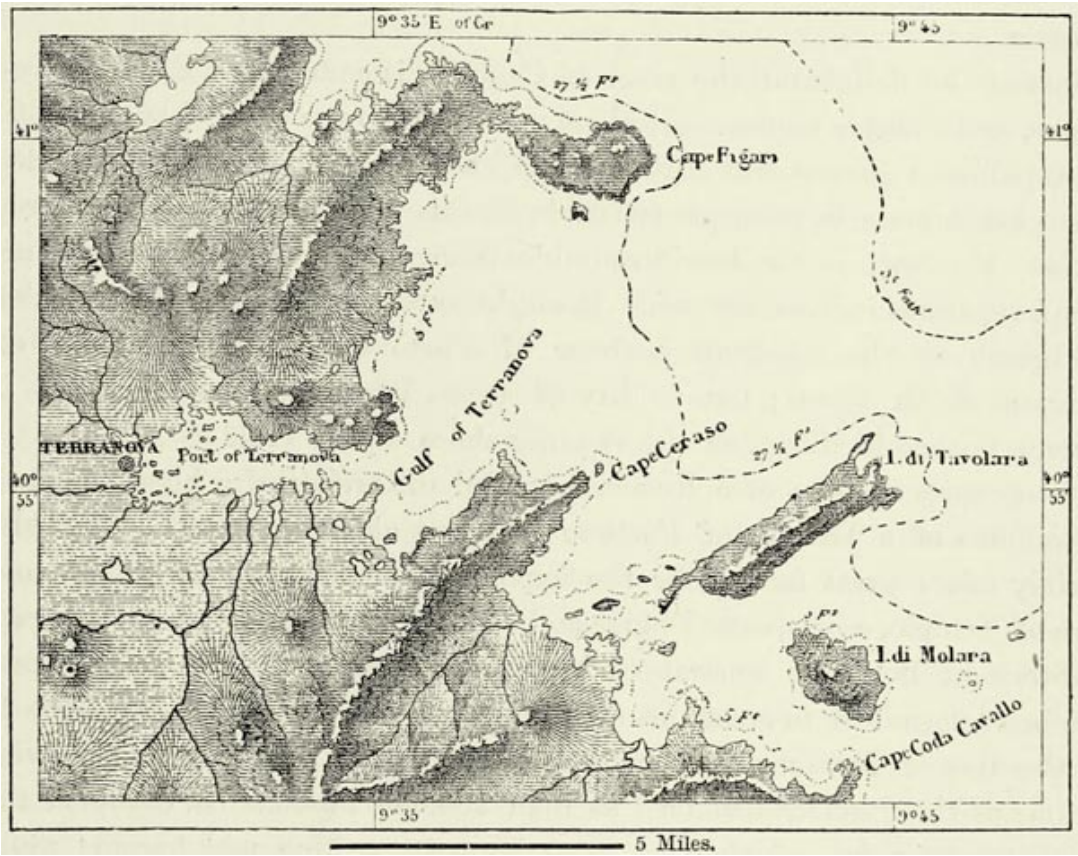
tunny-fish are sometimes caught in a single season. The swamps or lagoons likewise yield fish, which are caught in nets spread at the openings of the channels {350} communicating with the sea. The swamp of Cagliari abounds in shad, that of Oristano in mullets and eels, and that of Alghero in pike and gold fish. The fisheries of Sardinia are consequently of much importance, but most of their profits are reaped by strangers. Corsicans fish near La Maddalena, Genoese around San Pietro, and Italians monopolize the coral fisheries. These latter, too, collect the *Pinna nobilis*, a shell, the silky byssus of which is converted into stuff for garments. Nor do the Sardinians take to the sea as sailors, and the commerce of the island is carried on almost exclusively in Genoese and other Italian vessels. Out of 2,400 proverbs collected by Spano, only three refer to the sea! [118]

Fig. 129—CAGLIARI, AS SEEN FROM THE PASS OF BONERIA.

The inhabitants of the northern "Cape" of Sassari, or *di Sopra*, claim to be more intelligent and civilised than those of the southern "Cape" of Cagliari, or *di Sotto*. The former do not call themselves Sardinians at all, but apply that name, which to them is synonymous with barbarians, to the inhabitants of the {351} interior and of the south. In former times these two sections of the population hated each other, and the spirit of the vendetta, which set family against family, village against village, made its influence felt all over the island. This old animosity has not yet completely died out; but the

people of Sassari can no longer claim to be the superiors of their southern neighbours. They certainly are better agriculturists and more industrious, but the southerners possess the richest mines, their portion of the island is most productive, and it is the seat of the capital.

Fig. 130.—THE PORT OF TERRANOVA. M
Scale 1 : 250,000.



Cagliari, the ancient *Caralis*, has remained the great emporium of the island since the days of Carthage. Only a few idols, sepulchral chambers, the ruins of an aqueduct, and an amphitheatre excavated in the rock, recall the dominion of Carthaginians and Romans, but it could not be deprived of its excellent harbour and magnificent roadstead. The town was only a short time under the rule of the Moors, but its physiognomy is almost more oriental than that of any city in Europe, many of its houses being provided with cupolas and

balconies overhanging the streets. Its position as a place of commerce is most favourable, for it lies on the ocean highway connecting Sicily with the Balearic Islands, and the coast of Africa is within a day's sail. It is sure to prosper, especially if a serious effort is made to drain the marshes and to transform the plain of the Campidano into a fertile garden. The latter, an ancient arm of the sea, extends to the south-east towards Oristano, the "town of potters." During the Middle Ages {352} the latter was the seat of the most powerful lords of the island, and it was thence Eleonora promulgated her famous *Carta de logu*, which became the public law of the whole island. Oristano has an excellent harbour, sheltered by the peninsula of Tharros, upon which the Phœnicians had founded one of their settlements; its fields are fertile, and, to bring about a return of its ancient prosperity, it is only necessary to drain the marshes which now hem it in. In former times fires were lighted upon the walls of the town during the season of malaria, to purify the atmosphere; but the vast forests from which the fuel for these fires was procured have disappeared, and this portion of Sardinia is no longer entitled to its ancient epithet of "Arborea." It is said that in the marshes of Nurachi, to the north-east of Oristano, may be heard now and then a noise resembling the bellowing of a bull. This noise is probably produced by the passage of air through some subterranean cavern, and similar phenomena have been observed on the coast of Dalmatia.

Sassari the delightful, the rival of Cagliari, is embosomed amidst olive-trees, gardens, and country houses. It alone, of all the towns of the island, could boast of a republican government during the Middle Ages, and the public spirit of its present inhabitants is, perhaps, traceable to this circumstance. Its geographical position, however, is far less favourable than that of Cagliari, for a zone of swamps separates it from the sea. It might export its produce through the port of Alghero or the excellent harbour of Porto Conto, to the south of the mountains of La Nurra; but facility of access has

dictated its choice of Porto Torres, a miserable village on the swampy shore of the Gulf of Asinara. Porto Torres occupies the site of a Roman city, and the arches of a huge aqueduct and the columns of a Temple of Fortune still rise above the reeds. This old port certainly offers great facility for the export of the olive oil of Sassari and the wines of Tempio, as respects France and Genoa; but the intricate navigation of the Strait of Bonifacio separates it from the nearest Italian coast. Italy has therefore determined to create an additional port on the east coast of the island, and the Bay of Terranova has been selected for that purpose. *Olbia*, which at the time of the Romans had no less than 150,000 inhabitants, occupied the site of the present town, which the Italians fondly imagine may become the great emporium of the island. Its port is certainly well sheltered, and the roadsteads of the archipelago of La Maddalena near it afford additional accommodation; but seriously to improve the condition of Sardinia it will be necessary, above all things, to drain its dreary swamps, and to "transform their poisonous exhalations into bread."[119]

IX.—The Present and Future of Italy.

No impartial spectator can deny that Italy, since it has again taken its place among the nations of Europe, promises great things for the future. Even its {353} political regeneration has brought to the surface men of the highest intellect, courage, zeal, and public spirit. There are some amongst them whom posterity will look upon as a credit to all mankind. Possibly this period of excitement and nervous activity may be succeeded by a sort of moral collapse, such as generally takes place after every great crisis in the life of a nation. But this need not render us anxious for the future, for generations exhausted by the efforts they have made will be succeeded by others eager to continue the work their predecessors have begun.

In sciences and arts the native country of Volta, Cialdi, Secchi, Rossini, Verdi, and Vela occupies even now a position of equality with the most advanced nations of Europe. The Italian of the present day is able to refer without shame to the two great centuries of the Renaissance, for he has entered upon a second period of regeneration, and the names of contemporaries can be mentioned by the side of the great names of the past. Italy has its skilful painters and sculptors, its celebrated architects and unrivalled musicians. The great works achieved by its engineers are deserving the study of foreigners. Amongst its physicists, geologists, astronomers, and mathematicians there are some of the brightest ornaments of the age, and the assiduity with which universities are frequented insures their having worthy successors. A geographical society only recently established has successfully taken up the work of exploration so gloriously carried on by the Genoese and Venetians. It is not just, therefore, to say ironically that "Italy has been made, but not Italians." Individually the Italians are inferior to no other race of Europe, and the reorganization of the country would have been impossible had there been any deficiency in men of mark.

Italy is more densely inhabited than any other of the great states of Europe, in spite of vast extents of almost uninhabitable mountain tracts and swamps. The population, however, increases less rapidly than in Russia, England, or Germany. It doubles in about a century, whilst that of Russia doubles in fifty and that of France in two hundred years. Italy thus occupies an intermediate position. In Apulia and Calabria, which are amongst the poorest provinces, the birth rate is highest, whilst in the wealthy Marches and Umbria it is lowest. On an average the Italian dies when he is thirty-two, and his life is consequently much shorter than that of the average Frenchman or Englishman.

Agriculture and the development of the natural resources of the soil and the sea engage much more attention than industry properly so called. Nearly fifty per cent. of the total area is under cultivation. The cereals raised do not suffice for the wants of the inhabitants, but other products are exported in considerable quantities. In its production of oil Italy holds a foremost rank as regards quantity, but not always with respect to quality. The amount of fruit grown, such as figs, grapes, almonds, and oranges, is greater than in any other country of Europe. The chestnut forests in the Apennines and Alps yield rich harvests. Its mulberry plantations are four times more extensive than those of France, and the raw silk produced in favourable years exceeds in quantity that exported from China. The peninsula is still entitled to its ancient epithet of {354} Œnotria (wine land), but, apart from certain districts of continental Italy and Sicily, the quality of wine produced, owing to carelessness on the part of the growers, is inferior to what it is in France. The cultivation of cotton is comparatively of small importance. The breeding of animals yields large profits, and Italy is noted throughout Europe for the quality of some kinds of cheese.[120]

The working of the iron mines of Elba, the quarrying of marble and granite in the Alps and Apuanic Alps, the extraction of borax and boracic acid in the Tuscan Sub-Apennines, the mining for lead and

zinc in Sardinia, and for sulphur in Sicily,[121] lead up to industrial pursuits properly so called. These latter extend nearly to everything, from the manufacture of pins to the construction of steam-engines and ships. Italy, however, is eminent only in the production of certain *articles de luxe*, such as straw bonnets, cameos, coral jewellery, glass, and in the preparation of macaroni and other farinaceous pastes. The manufacture of silk, however, has taken a rapid development in recent years, and Milan has become a dangerous rival of Lyons. In the province of Novara, and more especially at Biella, there are hundreds of woollen factories. The cotton manufacture is not of much importance, and linen-weaving is for the most part carried on as a domestic industry. Italy, in fact, cannot yet be called a manufacturing country. The number of workmen is large, but they mostly labour at home or in small workshops,[122] and a division of labour, such as exists in England, France, or Germany, is hardly known. Manufactories, however, are rapidly increasing, and economical conditions are gradually becoming what they are already in most other countries of Europe.

Italy possesses a powerful mercantile marine, manned by 150,000 seamen; but its foreign commerce is far less than might have been expected from its tonnage.[123] Most of the vessels are engaged in the coasting trade. The first Italian vessel was seen in the Pacific in 1847, and even now the Italian flag is very inadequately represented in the navigation of the great oceans. Italian patriots are anxious to see the commerce of the country extended to the most distant regions. For the present Italy enjoys a sort of monopoly in the Mediterranean, and any increase of {355} population or wealth in Northern Africa must prove of immediate advantage to it. But there can be no doubt that the proposed railway from Antwerp or Calais to Saloniki or Constantinople will seriously affect the transit trade of Italian ports. Nor are Italian shipowners able to compete with their rivals of Marseilles or Trieste when it is a question of speed, for the number of their steamers is very small.

Fig. 131.—NAVIGATION OF ITALY. M

The facilities for carrying on coasting trade have, in some measure, interfered with the development of the inland trade of the country. The construction of railways, however, is gradually bringing

about a change. Already five lines of {356} rails cross the Apennines, others are projected, and one of the Italian railways, namely, that which pierces the Alps in the tunnel of Mont Cenis, and finally follows the eastern coast to Rimini, has become a portion of the great European highway to India. Nor must the political importance of these railways be underrated, for they knit together the most distant provinces of Italy, and make the country really one.[124]

Fig. 132.—ROUTES OF COMMERCE OF ITALY. M
Scale 1 : 6,000,000.

{357}

The commerce of Italy has increased rapidly of late, but it is still inferior not only to that of England, France, Germany, Austria, and

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